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Investigation of the trends of electricity demands in Jordan and its susceptibility to the ambient air temperature towards sustainable electricity generation

Ahmad Almuhtady[1*], Ahmad Alshwawra[1,2], Marwa Alfaouri[3], Wael Al-Kouz[4,3] and Ismael Al-Hinti[1]

Abstract

Background: Efficient production and reliable availability of electricity requires comprehensive understanding of load demand trends to plan and match production with consumption. Although electricity demand depends on a combination of cultural and economic conditions, weather conditions remain as the major driver. With increased capabilities of accurate predictions of weather, the importance of investigating and quantifying its impact on electricity demand becomes obvious. The electrical system in Jordan has been facing several challenges including the failure to respond to increased demands induced by extreme temperatures. This paper covers a clear gap in literature through presenting a detailed investigation of the electricity consumption trends and in identifying the susceptibility of these trends to weather.

Methods: This study relies on the statistical processing and analysis, through modeling of hourly electricity demands in Jordan in the period of 10 years between 2007 and 2016. Actual weather data was used employing the degree-day approach. The monthly, daily, and hourly seasonal variation indices were determined. Optimally formulated piecewise functions were used to track the thermal comfort zone and rate of increase in electricity demand for temperatures beyond it for each year. Moreover, the elasticity of polynomial functions was adopted to identify saturation points to thermally map the electricity consumption.

Results: The developed models successfully described the relationship between the daily electricity demand and the mean daily ambient temperature. The average comfort zone width was 4 °C and the average mean base temperature was 17.9 °C. The sensitivity of electricity demand to both high and low temperatures has increased on average, with 11% and 16.4% to hot and cold weather, respectively. Finally, the electricity demand in cooling was found to saturate at 32.9 °C, whereas it saturates for heating at 4.7 °C.

Conclusions: The electricity demand in Jordan observes seasonal trends in a consistent and predictable manner. An optimally formulated piecewise function successfully tracked the thermal comfort zone and the rate of increase in electricity demand for temperatures beyond it for each year of the study period. Finally, saturation heating and cooling temperatures were acquired from the elasticity of the daily electricity demands modeled against daily HDD and CDD.

Keywords: Electricity demands in Jordan, Electricity modeling, Seasonal variable index, Heating and cooling degree days, Thermal map, Sustainability in energy production

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* Correspondence: ahmad.almuhtady@gju.edu.jo
[1]Mechanical & Maintenance Eng. Department, German Jordanian University, Amman 11180, Jordan
Full list of author information is available at the end of the article

Background

Availability of reliably deliverable energy supply is critically important for economic growth, poverty reduction, and the social and cultural transformation of any society [1]. Electricity is considered as a high-grade energy carrier as it can be used to provide either power or heat directly [2]. As a matter of fact, both the production of all goods and services and the development of economic infrastructure depend on a reliable and sustainable supply of electrical energy [3, 4]. Nonetheless, electricity is difficult to store on a large-scale, and is mainly used instantaneously yielding to the fact that no or poor prediction for future electricity loads may lead to significant economic losses [2, 5]. The development of a low-carbon electricity network is constrained by the need to continuously address the shift in the balance of the supply and demand, especially in the residential sector, to achieve network stability [6]. Demand for electricity generally follows a cycle throughout the day that coincides with economic and social activities [7]. Nonetheless, addressing the deviation between peak demand and normal load can be challenging. Additionally, immerging and growing of (originally designed as a more sustainable solution) technologies such as electric vehicles (EV) can incur additional power demands coinciding almost exactly with the weekday daily load peak [8]. All of this promotes detailed investigation into the demand patterns and the major contributing factors such as weather, as in [9–18].

In general, one may observe three different seasonal patterns for the average daily electricity demand in countries throughout the world, namely, summer peak pattern, winter peak pattern, and two-peak pattern, one in summer and the other in winter. Winter peak pattern is mainly attributed to the increased heating demand as well as some increase in the demand in lighting due to shorter daylight periods. Summer peak is mainly led by the increased cooling applications in air conditioning and refrigeration. Higher temperature usually motivates more cooling demands as people's tendency to switch on air conditioning systems increases significantly. This is usually coupled with less efficient heat exchange in the aforementioned applications increasing naturally the demand on electricity the further the temperature increases beyond thermal comfort zone [13].

Many models are presented in literature to analyze the effects of temperature fluctuation on electricity demand. Models based on temporally aggregated measures of temperature, such as monthly average, suffer from two clear deficiencies, namely, the linearity's failure to capture the increase in demand at both very low and very high temperatures, and the monthly average temperature inadequate reflection for the usage during periods of temperature extremes in a given month [10]. Using a model based on employing heating degree-days (HDD) and cooling degree-days (CDD) [19], which measures the number of degrees that daily average temperature rise above or fall below a threshold value in a given period can help overcome the mentioned deficiencies [20]. The difficulties in applying this method are in the determination of base temperature and choosing a procedure for calculating degree days, which vary depending on the resolution of the weather data used [21].

Improving the results of such a model could be achieved by replacing the linear piecewise function used to predict the threshold temperature by more sophisticated non-linear functions. Examples are available in [5, 11, 14–16, 22, 23]. Even more, some of the literature provide more complex models to predict the impact of temperature fluctuation on electricity demands [10, 15, 24]. However, models that are more complex do not necessarily provide results that are more efficient [19, 25]. Based on that and on the fact that linear piecewise function models are still widely used, this paper will employ a CDD and HDD-based model with optimally formed linear piecewise function.

The Hashemite Kingdom of Jordan (latitude 32 N) is a Middle Eastern country with scarce fossil fuel resources; nonetheless, the electricity network covers the whole country. The electricity industry started in Jordan in 1937 when the country was known then as the Emirate of Transjordan. Since then, the electricity generation capacity in Jordan has been increasing to meet industrial and social developments, where in 2016 it was reported to be 4609 MW and the total generated electricity mounted to 19.73 TWh in the same year. More than 80% of this quantity was generated using imported natural gas [26], and 45% of the primary energy in Jordan was allocated for electricity generation [27]. The electricity load in Jordan usually follows the two-peak pattern. However, the maximum of those two peaks alternates from year to year based on weather conditions and fuel and electricity prices. For example, in 2015 Jordan had a summer peak of 3300 MW, while in 2016 it had a winter peak of 3250 MW [26].

The recent years had witnessed a rapid increase in Jordan's population, where the high rate of natural population growth coupled with the Syrian refugee waves guaranteed that. This added more pressure on the electricity system in Jordan. In 2016, the total electrical energy consumption in Jordan was 16.84 TWh [26], which amounts to 85.4% of the total electricity generated for which the majority of the losses occurring at the electrical distribution stage [28]. As shown in Fig. 1, about 60% was consumed by residential and commercial sectors. Those two sectors are the most susceptible to overlapping conditions like weather conditions, cultural and religious habits, population growth, fuel prices, etc. With increased capabilities of accurate predictions of weather conditions, the importance of investigating and quantifying its impact on electricity demand becomes evident.

The past few years witnessed several blackouts in many regions in Jordan during extremely hot and extremely cold

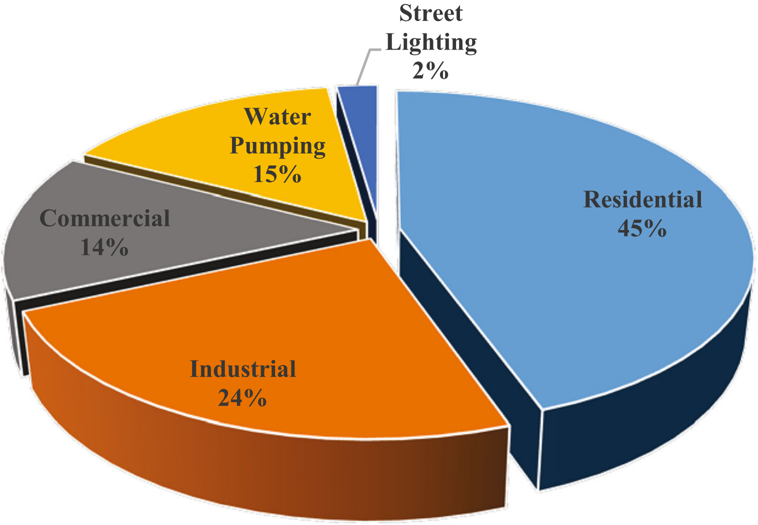

Fig. 1 Electricity consumption in 2016 by sector (figure generated from data available in [26])

days. Some of these losses continued for many hours causing economic losses and in some instances dangerous conditions in terms of heating, lighting, and security. The National Electrical Power Company (NEPCO) referred some of these blackouts to the extremely sudden load increases to the limits exceeding the generation capacity [29]. Despite that, there is a gap in literature regarding a detailed investigation of the effect of the weather conditions on electricity demand in Jordan.

For example, Al-Bajjali and Shamayleh [30] analyzed the electricity consumption in Jordan in perspective of the effects of gross domestic product, electricity prices, population, urbanization, structure of economy, and aggregate water consumption during the period 1986–2015. Utilization of the Johansen Cointegration test helped in examining the long-term relationships in their multivariate model, and then the Vector Error Correction model is utilized to show the impact of each determinant. Nonetheless, the authors recognized the influence of the temperature variation on the electricity consumption and stated it is not considered. El-Telbany and El-Karmi [31] utilized neural network model for short-term forecasting of Jordanian electricity demands. They trained their model by particle swarm optimization technique employing data of minimum daily temperature, the time factor, and previous demands values using NEPCO data in the years 2003 and 2004. After which, they tested their model through the prediction of 30 days electricity demands in November 2004. While the prediction achieved good agreement with the actual data for the month of November 2004, there is no indication of the capability of the model to successfully predict longer periods in addition to the fact that the model can be viewed as over-trained where 2 years of data worth was used for 1 month prediction. Moreover, using the minimum daily temperature in Jordan's weather can give a false indication about the actual daily temperature variation, especially in spring and autumn. This is why the mean daily temperature will be used in this paper.

Examples of other research work relevant to the prediction of electricity consumption in Jordan can be found in [32, 33] employing their own models, and in [34] employing readily available commercial energy models. Dar-Mousa and Makhamreh [28] represent another interesting example of research work exploring the pattern of electricity consumption and energy loss, to highlight the strengths and weakness of energy efficiency in the context of the urban sustainability of Amman City in Jordan. However, these research works either focused on a specific sector or ignored the effect of temperature in their models. Additionally, none of the mentioned research works studied the trends of electricity consumption in Jordan on a monthly, daily, and hourly basis.

The main contribution of this paper lies in a dual approach tackling the detailed investigation of the electricity seasonal consumption trends (monthly, daily, and hourly), in addition to identifying the susceptibility of this consumption to the weather conditions based on CDD and HDD models. All of which is studied throughout a period of 10 years between 2007 and 2016, and finally arriving at thermally mapped electricity consumption. Therefore, this work aims to serve as general state-of-the-art guidelines and a framework to people interested in the field of electricity generation and distribution including researchers, engineers, technicians, and installers. Moreover, it provides valuable information related to energy policy, energy planning, and energy economics and sustainability for the country Jordan. Finally, it is worthy to mention that the work is capable of providing base lines for future studies targeting the socio-economic energy consumption behavior of the Jordanian society in specific, and in the Middle East and North Africa (MENA) region in general. The analysis, results, conclusions, and proposed solutions are applicable to non-industrial countries, whose residential and commercial sectors dominate electricity consumption. Moreover, developing countries with climates similar to Jordan's can combine the understanding build upon the thermal map depicted at the end of this paper, with the monthly, daily, and hourly trends of electricity consumption explained in the next section, to plan for a more sustainable scalability of their energy generation scheme. The latter is key for any sustainability-inspired state policies.

Methodology

Data description

Electricity data

The electrical hourly demands were obtained from NEPCO for the period of January 1, 2007, to December 31, 2016. NEPCO is a state-owned company that is responsible for the construction, operation, and maintenance of the electricity transmission lines for the whole kingdom of Jordan [35]. NEPCO buys the electricity from private generation companies and sells electricity to distribution companies, which in turn sell electricity to the final consumers.

The investigated data consist of hourly electricity consumption combined from all sectors (residential, commercial, industrial, water pumping, and street lighting) for all Jordanian provisions throughout a period of 10 years between 2007 and 2016. The hourly data can achieve more accurate comprehension of the available trends. That is in addition to being easily aggregated to provide daily and monthly consumption trends, hourly data can shed the light on consumption trends within a specific day enabling more analysis on peak hours during weekdays and weekends. It should be reported that regional or sector-based disaggregated data were unavailable on an hourly basis.

Figures 2, 3, and 4 are intended to demonstrate the general trends of the electricity demand through periods of various lengths. Figure 2, which represents the evolution of total monthly electricity demands and monthly averaged ambient temperatures for the entire period under study, shows a continuous increase in electrical demand. This growth can be linked to demographical, economic, and social factors coupled with continuous waves of refugees from neighboring countries' war conflicts. The growth if not met by exploring new sources of energy (especially environmentally friendly ones) can become very dangerous as it will halt any further economic, social, or cultural development of the Jordanian society. For example, the government will be forced to either increase the prices of energy or generate it from health hazard sources. Additionally one can observe the evolution of the two-peak system, one almost persistently dominant developed coincidently with the extreme high temperatures, and another growing coincident with extreme low temperatures. The growth in the winter peak is evidently much faster and bringing it almost in level with the summer peaks in later years of the targeted period. This has two indications. The first is that more consumers are opting for electricity-based heating over fossil fuel-based heating. The second is that it reconfirms the significance of the share of the residential and commercial sectors in Jordan's electricity consumption, as other sectors will likely consume equal or less electricity in winter in comparison to the remainder of the year.

Unlike Fig. 2, Figs. 3 and 4 do not employ aggregated electricity demands and rather demonstrate it on hourly basis for a period of 3 years in Fig. 3 and a period of 1 week for Fig. 4. Inspection of the series reveals three clear seasonal patterns, monthly, weekly, and daily. This indicates that the consumption of electricity depends on the month

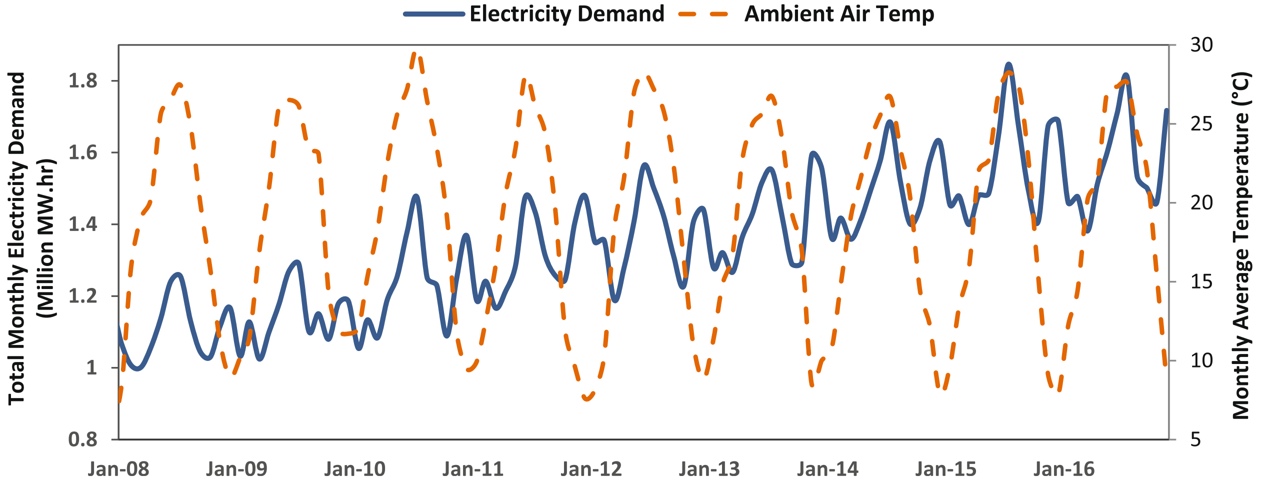

Fig. 2 Evolution of monthly electricity demand and temperature from 2008 to 2016

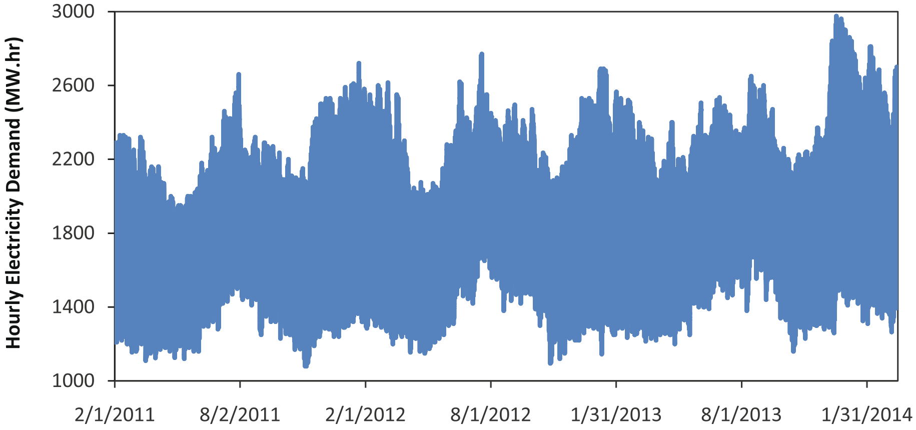

Fig. 3 Evolution of hourly electricity demand from Feb 2011 to Feb 2014

of the year, the day of the week and the hour of the day. To quantify this seasonality and interpret it through the lens of sustainability, monthly, daily, and hourly seasonal variation indices will be studied later on.

What should be noted is that monthly aggregated data (Fig. 2) has shown summer peaks always dominating their winter counterparts. However, if we are to examine the hourly peak demands from Fig. 3, winter and summer amount to close maximum levels. The main reasoning behind this is that the aggregated monthly data combines all of the hours including the low consumption ones (around night time), which from Fig. 4 can be seen higher for summer weeks as consumer activities are not diminished by night time. Finally, hourly trends are clear from Fig. 4 where within a specific day, maximum demands are around midday with a consistent dive downward right up to the hour prior to the light switching on (7 pm for summer and 4 pm for winter). Further in depth analysis and examination of the trends is available in the "Data processing and analysis" section.

Weather data

To examine the weather effect on the electricity consumption, literature has concluded that the air temperature is the most critical weather variable in comparison to other factors such as humidity and wind speed [36–39]. Additionally, countries' electricity demand, where residential and commercial electricity consumption is significantly dominant, is susceptible to weather variations within the populated regions, as climate influences the electric consumption through the response of people to weather [5].

Jordan is comprised of 12 governorates and is divided based on the bio-climatic criteria into four zones: Desert area, steppe region, highland, and the Jordan valley. Despite that, the population is mainly concentrated in the highlands and steppe region [40, 41] as can be seen in Fig. 5 and Table 1.

It was demonstrated in previous researches that when the available electricity consumption data are not regionally disaggregated, a population-weighted temperature index PTI (°C) constructed from several weather stations located

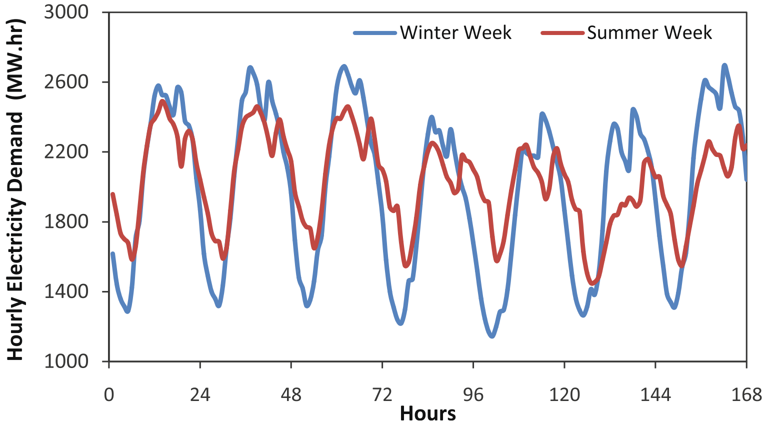

Fig. 4 Evolution of hourly electricity demand for a winter week (Jan 6–Jan 12) and a summer week (Jul 7–Jul 13) in 2013

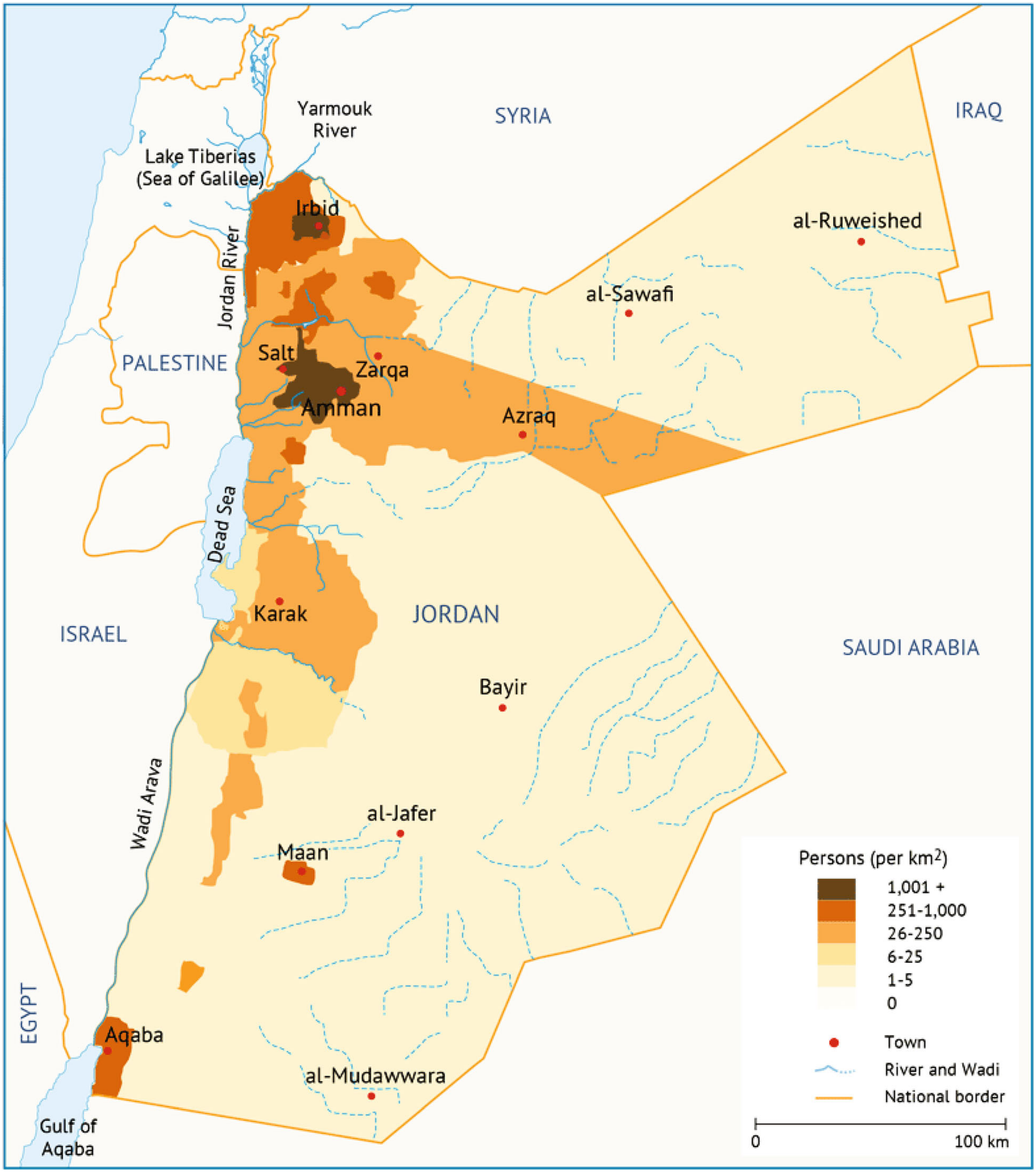

Fig. 5 Population density in Jordan [30]

near high-population density regions can successfully capture the electricity consumption susceptibility [5].

Therefore, PTI was calculated for Jordan using data from six weather stations within governates (Amman, Irbid, Zarqa, Karak, Madaba, and Ma'an) accounting for more than 81% of the total population [41]. Compared against the ambient air temperature of Amman (Marka) airport weather station at randomly selected times and days of years 2011 and 2014 (see Fig. 6), it can be seen that the deviation from the 45 degrees line is minimum. Additionally, daily mean PTI was calculated and compared against daily mean temperature of Amman. Table 2 demonstrates that

Table 1 Population in Jordan based on governorate and bio-climatic region in 2014 [40]

Year	Population	Population concentration bio-climatic region*
Amman	3,701,500	1 and 2
Irbid	1,634,900	1 and 2
Zarqa	1,260,700	2
Mafraq	508,000	2 and 3
Balqa	454,200	1 and 4
Karak	292,500	1,2, and 4
Jarash	219,000	1
Madaba	174,800	1 and 2
Aqaba	173,800	2 and 4
Ajlun	162,600	1
Ma'an	133,100	3
Tafiela	88,900	1 and 2

(*)1-highland 2-steppe region 3-Desert area 4-Jordan valley

the average deviation (ΔT) between the daily mean temperature in Amman and daily mean PTI for Jordan through several years is very small registering a maximum value of 0.41 °C in 2013. The standard deviation $\sigma(\Delta T)$ in the average daily difference also confirms that. The max deviation (ΔT_{Max}), and minimum deviation (ΔT_{Min}) assures us that the deviation is reasonably bounded and is subjected only to random error. This indicates that the mean temperature in Amman is very representative of the populated Jordan and fit as a proxy.

That is, Amman is not only the political capital of Jordan, but also the economically and demographically central city of Jordan where more than half of the population resides and works and with medium weather conditions between relatively hotter desert parts and colder highland ones makes it an excellent representative of Jordan's PTI weather at a given time of the day (Fig. 6) or the mean daily air temperature (Table 2). In conclusion, the temperature in Amman can be by far considered a representing active population-wise temperature for all of Jordan due to its unmatched share of Jordan's population and civilization.

*1, highland; 2, steppe region; 3, desert area; 4 Jordan valley

Data processing and analysis

To further investigate the available trends in the electricity data independently of the weather conditions, the following seasonal variation indices are calculated: monthly, daily, and hourly. The Monthly Seasonal Variation Index (MSVI) shows the relative behavior for each month with respect to the rest of the year. It is defined as the total electricity consumed in a month of a given year divided by the average monthly consumption in that year,

$$\mathrm{MSVI}_{ij} = E_{ij}/\overline{E_j} \tag{1}$$

where MSVI_{ij} is the index value for month i in year j, E_{ij} is the total electricity consumption for month i in year j, and $\overline{E_j}$ is the monthly average electricity load for year j [5].

Figure 7 shows the average, maximum, and minimum MSVI values for each month of the year for the period of study. The monthly seasonality presents a decreasing in electricity demand from January to April where it starts to increase again until August, then another decrease until November, and lastly the demand increases in December. This confirms the fact that increased electricity demands occur during extreme weather conditions (cold winters and hot summers) whereas decreased ones are around spring's and fall's moderate temperatures. This highly promotes the second main part of the paper, namely, the detailed investigation of the weather's effect on the electricity demands.

The trends of the minimum and maximum MSVIs indicate consistency in the monthly seasonality. That is, even the fact that there is a continuous increase in the electricity demand yearly as indicated earlier, each month exhibits similar relative values respective to its year. The difference between the minimum and the maximum values reveals the deviation from the mean average behavior. This deviation takes place at extreme weather months confirming electricity demands susceptibility to weather. We note that the reason why the demand represented by MSVI in March is higher than the one in February, despite being more moderate in temperature, is due to the number of days in each month. That is MSVI takes into consideration the total electricity consumed in the month which is impacted by February being 28 days while March 31 days in the majority of the years. Figure 8, which is only concerned with MSVI for leap years (2008, 2012, and 2016), demonstrates that the curve continually decreases in the expected manner from February to March.

To illustrate further Jordan's moving from one summer peak pattern to two peaks, summer and winter, pattern, Fig. 9 shows the MSVI for 2007 and 2016. It could be clearly seen that the winter months' MSVI (December, January, and February) in 2016 is higher than 2007, while the summer months' MSVI remains the same.

The Daily Seasonal Variation Index (DSVI) shows the relative behavior for each day with respect to the rest of the week. It is defined as the total electricity consumed in a day of a given week divided by the average daily consumption in that week,

$$DSVI_{ij} = E_{ij}/\overline{E_j} \tag{2}$$

where DSVI_{ij} is the index value for day i in week j, E_{ij} is the total electricity consumption for day i in week j, and $\overline{E_j}$ is the daily average electricity load for week j [5].

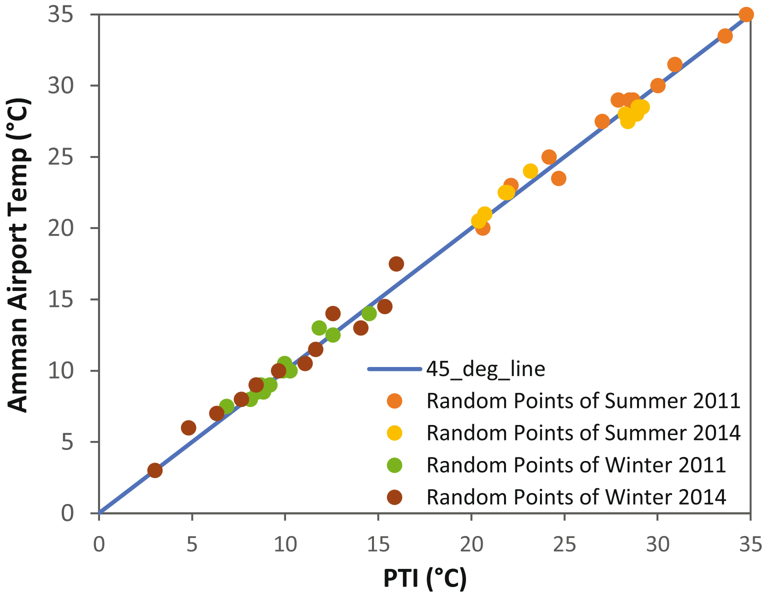

Fig. 6 Amman Airport temperature vs. population-weighted temperature index in Jordan [30]

Weekend in Jordan usually points out to Fridays and Saturdays despite Friday being the only official weekend in Jordan. That is Saturday is an off day for governmental organizations and administrations, banks, schools, universities and some private institutions, whereas many of the firms in the private sector work on Saturday. It is also worth knowing that Thursday is a shortened working day for many firms in private sector especially if they operate on Saturdays. This boils down to Sunday through Wednesday being full working days with almost all sectors actively contributing in the electricity demand, whereas Thursday and Saturdays will be short of that and finally Friday being the nearly unanimous minimum activity day.

The previous setup projects the specific behavior of the DSVI trend seen in Fig. 10. The average DSVI is almost constant from Sunday to Wednesday, then it falls in Thursday reaching its very minimum values on Friday, before it raises again on Saturday. DSVI values for Thursday and Saturday are lower than the rest of the working days. One additional interesting fact related to the DSVI minimum curve is that it coincides with holidays placed within the weekdays. Moreover, electricity demands decrease for holidays placed around the weekend where it almost matches the Friday minimum value.

Table 2 Benchmarking the daily mean temperature in Amman against PTI for Jordan in degrees Celsius

Year	ΔT	ΔT_{Max}	ΔT_{Min}	$\sigma(\Delta T)$
2013	0.41	2.89	−2.06	0.53
2014	0.38	2.37	−2.79	0.53
2015	0.31	1.59	−1.09	0.45
Average	0.37	2.28	−1.98	0.51

The Hourly Seasonal Variation Index (HSVI) shows the relative behavior for each hour with respect to the rest of the day. It is defined as the total electricity consumed in an hour of a given day divided by the average hourly consumption in that day,

$$\mathrm{HSVI}_{ij} = E_{ij}/\overline{E_j} \tag{3}$$

where HSVI_{ij} is the index value for hour i in day j, E_{ij} is the total electricity consumption for hour i in day j, and $\overline{E_j}$ is the hourly average electricity load for day j.

Figure 11 shows the mean, maximum, and minimum HSVI values for the weekdays without holidays (left) and the weekends (right) for the entire period under study. The electricity demand on weekdays increases continuously after 4:00 am where early morning prayer is the most viable candidate for such an early kick-off of the active region. The increase continues until 11:00 am after which it almost flattens out until 19:00 (7:00 pm), before it starts decreasing continuously until 3:00 am. This implies that Jordanians observe the highest electricity-consuming activities during the day. It is interesting to note that curve observes different behavior on weekends where the kick-off starts later and the curve crosses the unity 1 hour later in comparison to the weekdays. The point marked by the circle represents a major blackout in a wide region in Jordan on January 14, 2014. The figure shows as well the trend if the blackout is eliminated from the data.

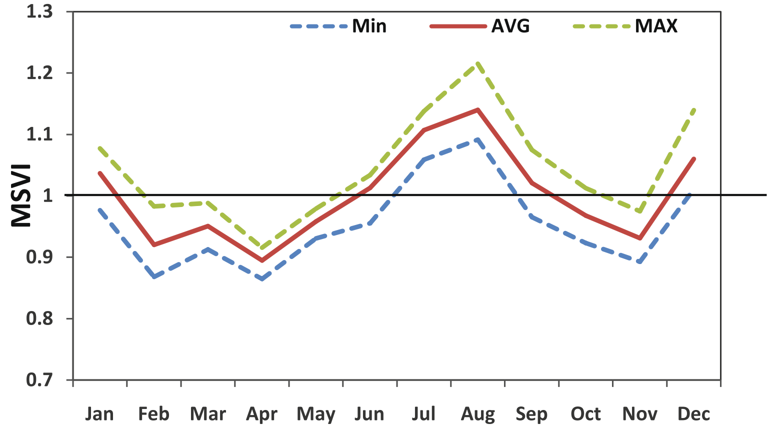

Fig. 7 MSVI for electricity demand from 2007 to 2016

The HSVI index is highly susceptible to the season in general and the ambient air temperature in specific (Fig. 12). In summer weekdays (right), one can notice two peaks, a day peak around 2 pm and an evening peak around 8:00 pm, while in winter a clear night peak took place around 6 pm. The summer peaks are attributed to the large air conditioning load during working hours for the 2 pm and the start of the night activities with light switched on for the 8 pm peak as has been discussed earlier. With a daylight-saving system, the lights switch on earlier in the winter increasing the HSVI from 3 pm to 5 pm.

It is worthy to mention that upon observing the maximum and minimum trends of the winter and summer HSVI, the deviation is much higher for the winter indicating conformity in Jordanians activities during the day in the summer throughout the 10 years study period, whereas the activities demand on electricity varied in winter days. The consistent valley noticed in summer HSVI at 6 pm is attributed to turning off the air conditioning units at that period in summer due to ambient air temperatures moving towards moderate levels, a key characteristic of Mediterranean dry weather.

In light of all the indices shown, achieving sustainability in electricity generation with respect to the seasonal variations in demand is achievable with creating a sufficiently diverse and capacity-adjustable energy mix to sustain maximum efficiency. For example, at the end of 2016, natural gas accounted for 84% of the resource from which electricity was generated, whereas the renewable energy share did not exceed 5% [26]. Not only does this recipe oppose sustainability in the general term for obvious economic and logistics reasons, but also scaling up electricity generation by gas turbines and combined cycle power plants is not easily nor efficiently attainable. It is without any doubt that the increase of the share of electricity generation by renewable energy is crucial for sustainability. The renewable energy share must be able to account for short-term demand variations and must be scalable to account for increasing demand depicted in Fig. 1.

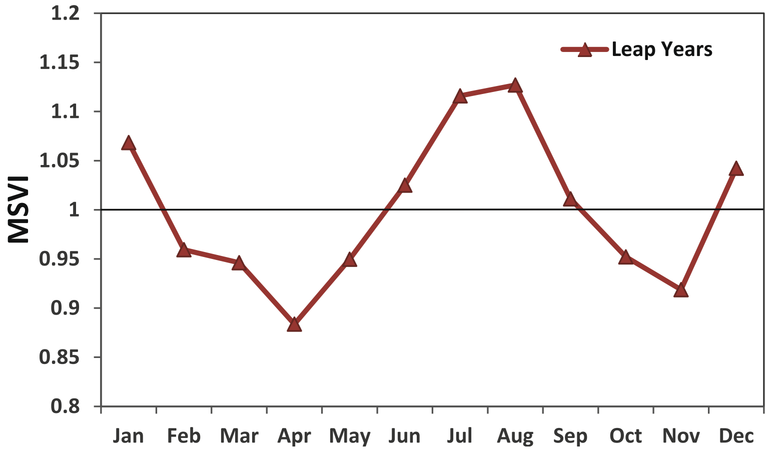

Fig. 8 Average MSVI for leap years only

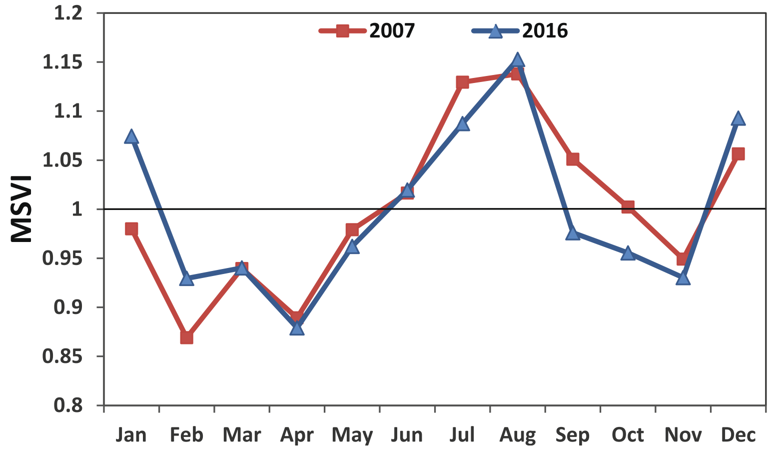

Fig. 9 MSVI for 2007 and 2016

Model description

Monthly HDD and CDD are calculated using the following formulas:

$$\mathrm{HDD} = \sum_{i=1}^{M} (T_{\mathrm{base}} - T_i),\ T_i \le T_{\mathrm{base}} \tag{4}$$

$$\mathrm{CDD} = \sum_{i=1}^{M} (T_i - T_{\mathrm{base}}),\ T_i \ge T_{\mathrm{base}} \tag{5}$$

where M is the number of days in a month, T_i is the daily average temperature of the day *i*, and T_{base} is the base temperature. The base temperature is determined for each year using a piecewise linear fitting method. The model function comprised of three main segments: a middle region where the electricity demand is independent of temperature for each year represented by a straight horizontal line, and two adjacent regions (right and left of the horizontal line) comprised of inclined lines representing the electricity demand increases with temperature. The best continuous set of straight lines that fit the data was targeted. The fitting was accomplished through the least square method with optimization that targets minimizing the sum of the squares of the differences between the model values and the total daily electricity demands from the real data at all mean daily temperatures. A constraint was placed on the horizontal segment representing the comfort zone with a minimum length of 1 °C rendering the optimization at hand as constrained non-linear optimization. The optimization algorithm employed is the Sequential Quadratic Programming (SQP) algorithm as it is capable of delivering more speed on small- to medium-sized problems. As the behavior for the electricity demand changes from weekdays to weekends, temperature bases were acquired for each separately.

In addition to the model's capability to show how the base temperature and comfort zone changes over years, the sensitivity of electricity demand to cold and

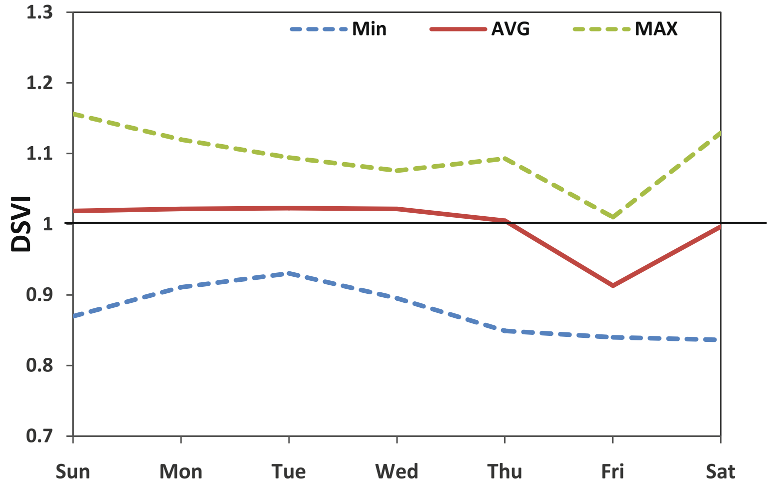

Fig. 10 DSVI for electricity demand from 2007 through 2016

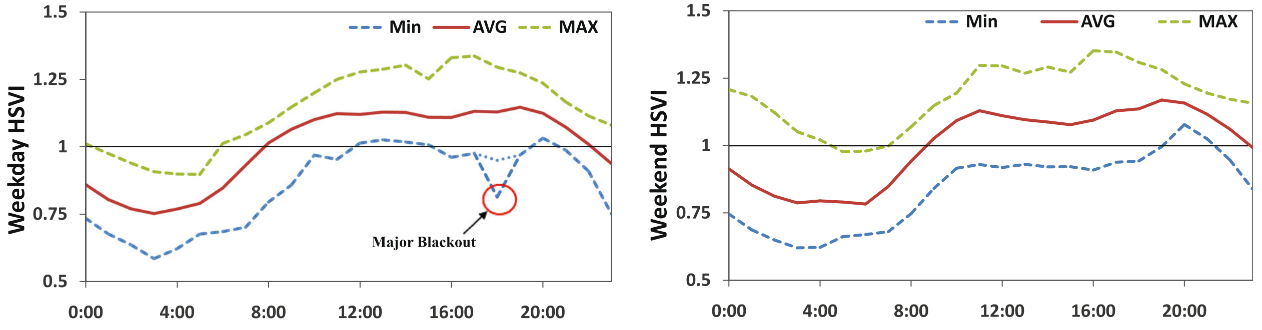

Fig. 11 HSVI for electricity demand during weekdays (left) and weekends (right) from 2007 to 2016

hot temperatures can then be deduced from the slope of the best-fit lines.

After finding the CDD for hot months and HDD for cold months, daily electricity demand was plotted against daily CDD and daily HDD for each year to find the effect of increasing HDD and CDD on the electricity demand. Polynomial fits of the functions were obtained.

$$\varepsilon_{\mathrm{HDD}} = \mathrm{HDD}\frac{f'(\mathrm{HDD})}{f(\mathrm{HDD})} \tag{6}$$

$$\varepsilon_{\mathrm{CDD}} = \mathrm{CDD}\frac{g'(\mathrm{CDD})}{g(\mathrm{CDD})} \tag{7}$$

Finally, the elasticity was plotted against the HDD and CDD to find the heating and cooling saturation points for each year.

Results and discussions

Figure 13 shows the piecewise function fits for the models describing the relationship between the daily electricity demand and the mean daily temperature for the years 2007, 2010, 2013, and 2016. The process was repeated for all the years under the study period and for the weekdays and weekends separately. It can be seen clearly that the optimization algorithm successfully converges to the best set of lines described in the model where the slopes of the inclined lines represent the heating and cooling sensitivities and the start and end of the horizontal lines mark the heating base temperature and cooling base temperature, respectively. In each of the cases, the iterative optimization algorithm registered exit flags specifying that the change in the model variables was less than the tolerance setting value of 10–15, indicating successful convergence.

Figure 14 summarizes the resulted base temperature and comfort zone for each year in the study period for the weekdays. It is noted that the comfort zone changes from year to another because of the change of the aggregated social response to high and low temperature in addition to the governmental intervention through electricity and oil-based fuel prices.

The average base temperature for HDD was 15.8 °C with a minimum of 13.5 °C in 2007 and a maximum of 18 °C in 2009. For CDD, the average base temperature was 19.9 °C with a minimum 19 °C in 2007 and a maximum of 21.2 °C in 2016. That means the deviation from the average in the base temperature for HDD is much larger than CDD, indicating that the change in electricity consumption as a response for cold temperature is subject to other factors in comparison to the response for the hot temperature. Heating can be achieved through several means and electricity is just one of them.

The average width of comfort zone was 4 °C with a minimum of 1 °C at 2009 and maximum of 6.1 °C at 2013. The average mean base temperature (blue dotted

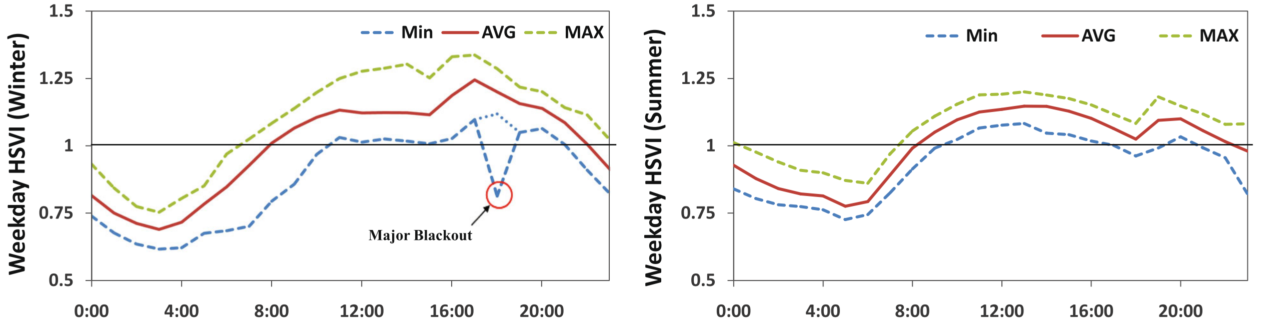

Fig. 12 HSVI for electricity demand during winter weekdays (left) and summer weekdays (right) from 2007 through 2016

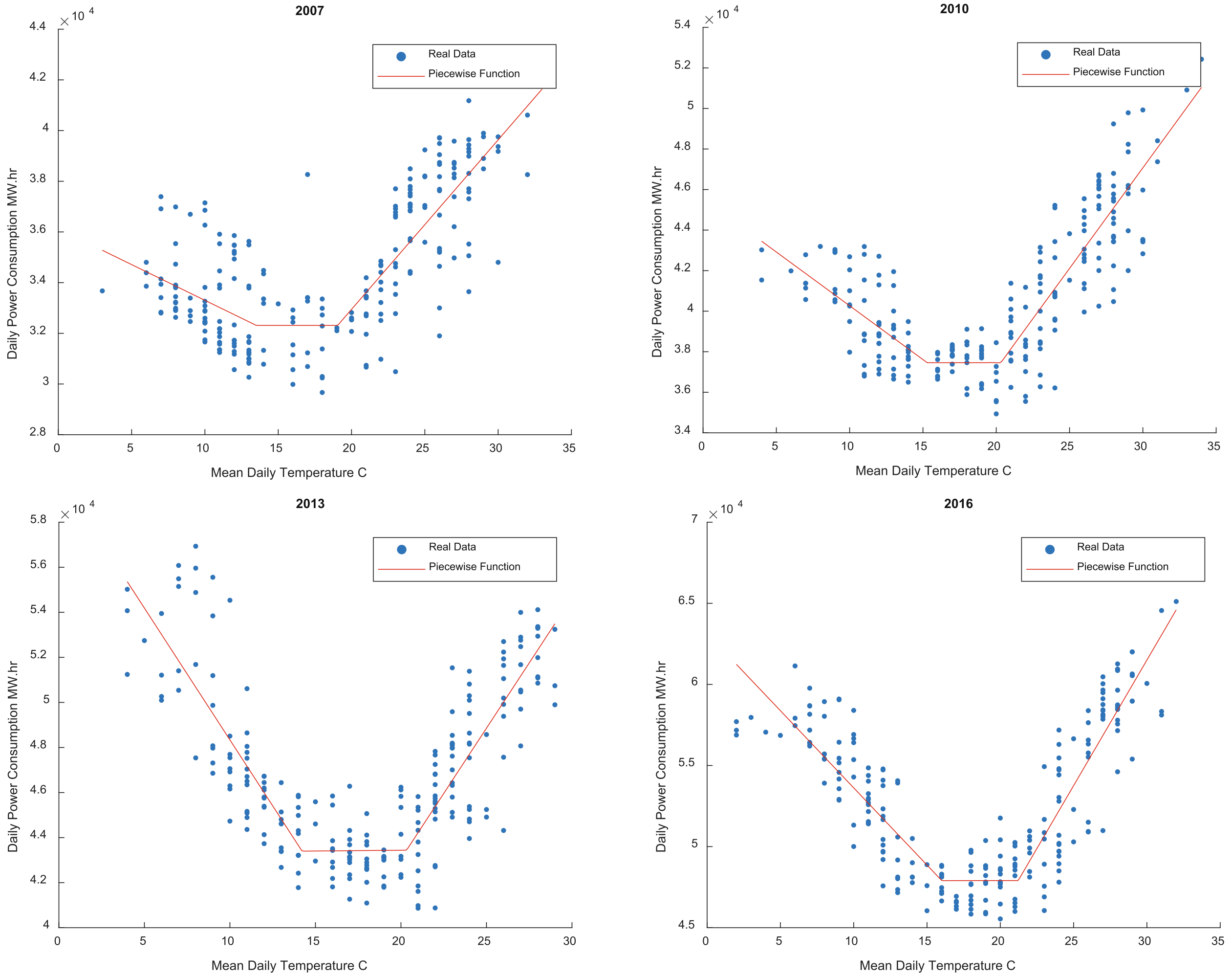

Fig. 13 Examples of piecewise function fits for the daily electricity demand vs. mean daily temperature

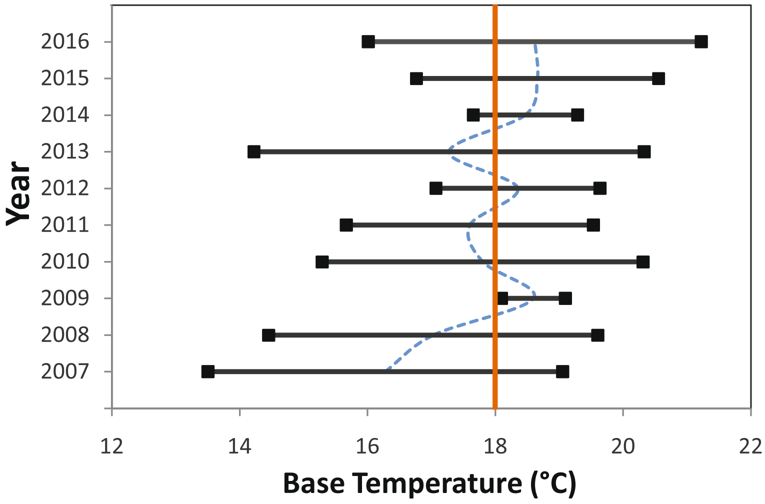

Fig. 14. Base temperature eanges for the weekdays for the years 2007–2016

line) was 17.9 °C with a minimum of 16.3 °C in 2007 and maximum of 18.7 °C in 2015. The mean base temperature is the arithmetic mean for HDD and CDD base temperatures for each year. The average value for the mean base temperature agrees strongly with the value of 18 °C, used commonly in literature throughout the past 30 years [5, 23, 25, 42–44], validating the model and results.

The slope of the best-fit lines in heating and cooling regions represent the susceptibility in general and the active sensitivity in particular of electricity demand to the increase or decrease in temperature beyond comfort zone. The slopes from the years of interest are plotted in Fig. 15. It was noted that there was an increase in electricity consumption of 669 MWh for each degree increases above the CDD base temperature in 2007. This sensitivity increases with almost a constant rate of 79.2 MWh/°C/year until the end of 2013. In 2014, a decrease in sensitivity by 7% was noted due to the sudden increase in electricity prices compared with the previous year. The electricity prices increase shock was eventually overcome in 2015 and 2016, due to the increase in ambient air temperature in the hot summers of those 2 years where the sensitivity trend was restored. The average growth in the sensitivity to high temperature was 11% for the whole period of study. The growth in the sensitivity is attributed to two main factors: population increase and increased susceptibility. That is while the former one dominates the increase due to the high rate natural population growth coupled with waves of refugees, it cannot encompass the nearly consistent growth in sensitivity which uncovers increased consumers susceptibility to hot weather (i.e., more people are turning their air conditioning systems in hot weather).

Regarding the sensitivity to the cold weather, it was noted that there was an increase in electricity consumption of 282 MWh for each degree decrease below the HDD base temperature in 2007. The trend of the sensitivity was increased by 125.5 MWh/°C/year until the end of 2013. Once again, 2014's increased electricity prices lowered the sensitivity before it increased again in 2015 and 2016. The average growth in the sensitivity to cold weather was 16.4% for the whole period of study. It is higher than the average growth in the sensitivity in the hot weather, which supports the assumption of increasing the tendency to use electricity in heating applications.

The number of CDD and HDD for each year depend on multiple factors including the weather conditions in that year. They are calculated based on Eqs. (4) and (5) and are shown in Fig. 16. The average number of yearly CDD is 920 °C day with a minimum of 725 °C day in 2013 and maximum of 1107 °C day in 2010. While the average number of HDD is 782 °C day with a minimum of 420 °C day in 2010 and maximum of 1036 °C day in 2012. Again, the deviation from average in HDD is larger than CDD. It is worth to mention that the minimum number of HDD in 2010 was associated with higher winter temperatures in that year as shown in Fig. 2. Also, the number of HDD was less than the number of CDD (except for 2015) reflecting Jordan's hot summers and slightly cold winters.

The heating $f(x)$ and cooling $g(x)$ functions, which link the daily electricity demand with the daily HDD and the daily CDD, can be obtained from polynomial best fits. Figure 17 shows this for 2016. The elasticity (ε) of the heating and cooling functions at each daily temperature difference can be then found from Eqs. (6) and (7). Figure 18 shows the elasticity trends for the year 2016 for Jordan in addition to the elasticity trend for Spain obtained from [5]. The agreement in the saturation temperature validates further the results. That is, the elasticity function demonstrates the saturation point after which the increase in ambient air temperature (in summer) or the decrease (in winter) beyond the cooling and heating saturation temperatures, respectively, no longer propels a significant increase on electricity demand.

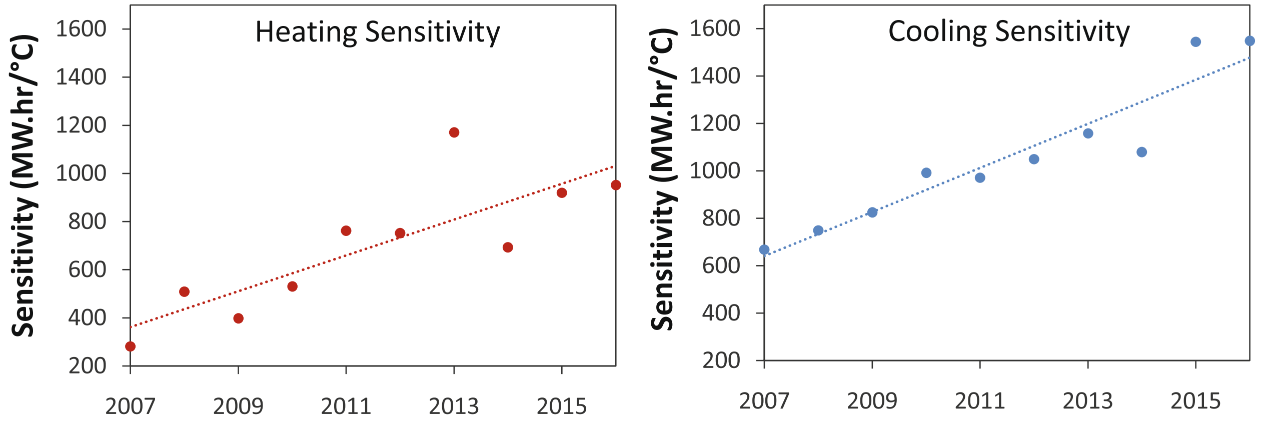

Fig. 15 Heating and cooling sensitivities for the years 2007–2016

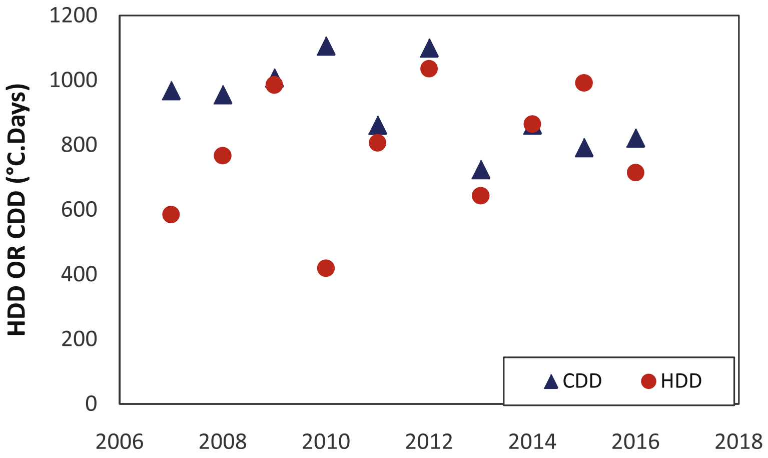

Fig. 16 Heating and cooling days for the years 2007–2016

Therefore, the thermal map covering all ambient temperature values and how the electricity demand's susceptibility to it plays out to five distinct regions (Fig. 19). The middle area bounded by the heating and cooling base temperatures is unaffected by the ambient air temperature and is called the comfort zone. In this region, the moderate and very close to human ideal environment promotes no use of electricity to actively control the air temperature and the electricity demand is propelled by the customers other activities.

On the right and left to the comfort region are the active cooling and active heating regions, respectively, where the more the ambient air temperature moves beyond the corresponding base temperature, the more electricity is demanded by consumers who are actively turning on any form of air conditioning or heating. This is deduced from the diversity in the human behavior. For example, at a few degrees Celsius higher than the cooling base temperature, a few consumers are inclined to turn on their air conditioners. With hotter weather, this percentage increases. The increased electricity demand is then met by a boundary beyond which the increase diminishes. Beyond this boundary, saturated heating and saturated cooling regions are located. The electricity demand flattens within these regions and is again insensitive to the ambient air temperature.

For example, taking the cooling for the year 2016 as an instance, the saturation occurs around a mean daily air temperature of 35 °C. The increased tendency of consumers who were opting to turn on their air conditioners beyond the 2016 cooling base temperature of 21.2 °C will saturate at 35 °C rendering the electricity demand increases beyond that minimal and mainly attributed to lower air conditioning efficiencies (COP).

On average, it was found that the electricity demand in cooling saturates at a mean daily ambient air temperature of 32.9 °C whereas it saturates for heating at 4.7 °C. These results have a good agreement with previous work in Spain [5] where the cooling saturation temperature was about 32 °C and the heating saturation temperature was about 2 °C. The deviation in the heating saturation temperature is attributed to nominally colder weather in Spain.

Finally, it is important to mention that the width of the comfort zone is subjective to economic and social factors. For example, the economic flourishing in the

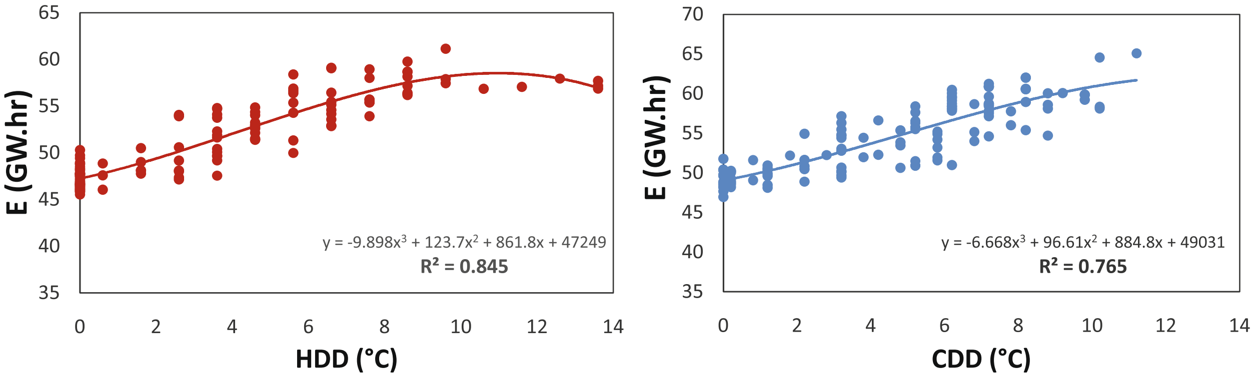

Fig. 17 Daily electricity demand vs. daily HDD and CDD for the weekdays of the year 2016

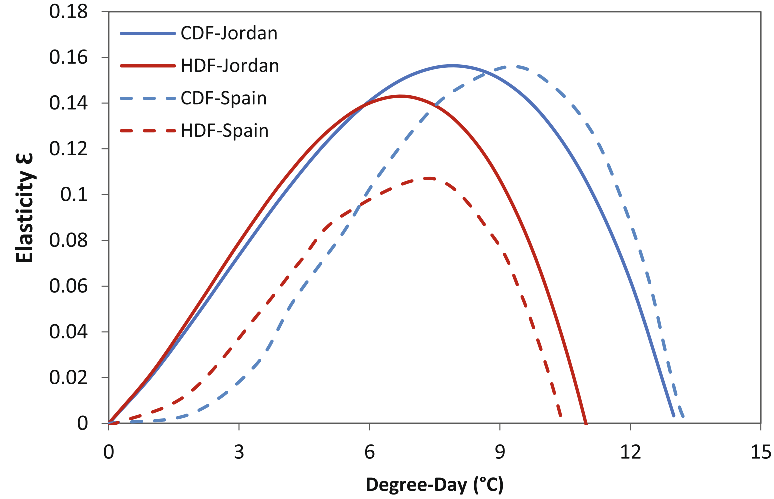

Fig. 18 Elasticity functions calculated for the heating and cooling demand functions (HDF and CDF) for Jordan (2016) and Spain (1998) [5]

years 2010–2013 has narrowed it as many consumers felt economically comfortable to demand electricity for minor deviation from optimal temperature, whereas the governmental intervention by increasing the electricity prices at the end of 2013 and starting from 2014 has widened it again. The tendency to switch on air conditioning systems decreased.

Not only can the findings here be assistive to the success of any electricity demand forecasting model for Jordan, but also they have key value for sustainability acquired by keen decision-making and strategic planning on the short term and long term, on a small scale and on a state level as well.

For example, a crucial component of a resource's sustainability is the healthy operability. The continuous maintenance of electricity systems (generation, transmission, and distribution) guarantees minimal losses and sustainable delivery. In light of the findings here within the thermal map, it would be ideal if most of the extensive maintenance operations are planned and conducted when the ambient temperature for successive days are predicted to be within the thermal comfort zone. On the contrary, planning for servicing the equipment during active heating or cooling regions might be risky where the demand is non-constant as explained earlier and

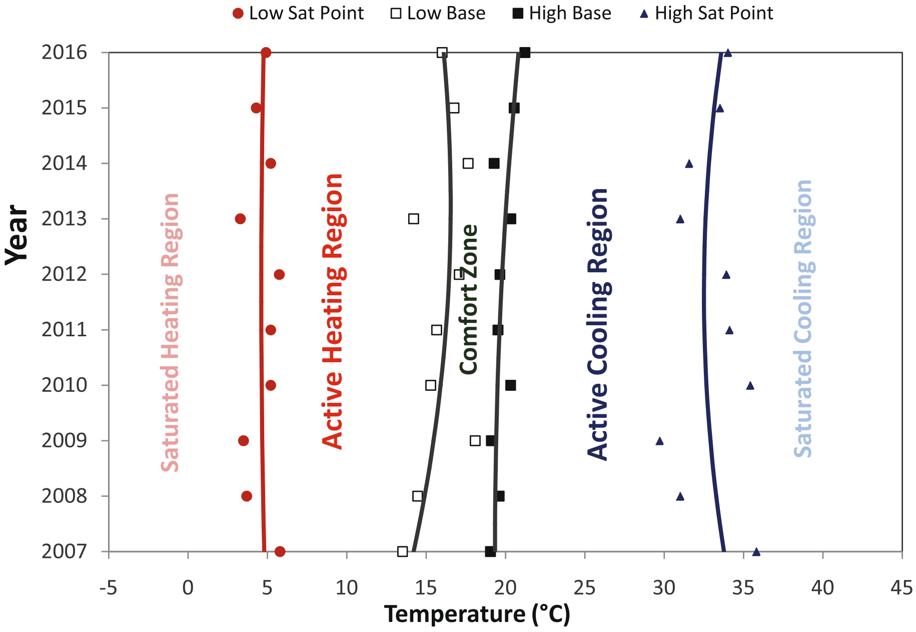

Fig. 19 Thermal map comprised of comfort zone, and saturated and active heating and cooling regions for the years 2007–2016

fluctuates upon social and economic factors. As a matter of fact, the findings here propose that having maintenance operations within the saturation region (high and low ambient temperatures) is even less riskier, as the demand saturates to constant levels, despite the probability of not being able to meet it entirely. This is just one example of how the findings here can provide knowledge and insights that enables more intelligent decision-making, foresight planning, and more resilient and sustainable performance.

Conclusions

This paper tackled two main topics in terms of electricity demands in Jordan in the period of 10 years between 2007 and 2016. The first mainly focuses on identifying trends and seasonalities, and the second focuses on defining the susceptibility of the electricity demands to the ambient air temperature.

For the first, it was concluded that the electricity demand in Jordan observes seasonal trends represented by demands changing over the different months of the year in a consistent manner throughout the study period. Two main peaks (winter and summer) were identified each year with the peaks themselves increasing on a yearly basis due to the increase in demand. Other trends represented by daily and hourly indices were identified. Friday represented the lowest demand of the week with both Thursday and Saturday having lower values than the rest of the weekdays. Hourly data revealed a trend of increased demand from early morning for weekdays and later for weekends till noon where it saturates for a while and then drops down right before the sunset. These trends and seasonalities, which are key for any forecasting models, demonstrated that the current energy mix and fuel options for generating electricity cannot achieve sustainability for their lack of scalability and adjustability.

For the second, the ambient air temperature of Amman was verified to be a proxy for the whole country and the electricity demand susceptibility to it was modeled. An optimally formulated piecewise function was used to track the thermal comfort zone and the rate of increase in electricity demand for temperatures beyond it for each year of the study period. While the average center of the thermal comfort was in strong compliance to the 18 °C default value in literature, the comfort zones were changing depending on social and economic factors such as the fuel and the electricity prices especially in the heating. The heating base temperature was suffering the most deviation with an average of 15.8 °C with a minimum of 13.5 °C in 2007 and a maximum of 18 °C in 2009. The average cooling base temperature was 19.9 °C with a minimum 19 °C in 2007 and a maximum of 21.2 °C in 2016. The sensitivity of the electricity demand for ambient air temperatures was increasing from year to year by 79.2 MWh/°C/year for cooling and by 125.5 MWh/°C/year for heating except for the year 2014 where the governmental intervention by raising electricity prices dominated the consumption trend.

Finally, saturation heating and cooling temperatures were acquired from the elasticity of the daily electricity demands modeled against daily HDD and CDD. It was found that the electricity demand in cooling saturates at an average mean daily ambient air temperature of 32.9 °C, whereas it saturates for heating at 4.7 °C.

Upon all of this, the following technical and economic recommendations are offered. The pricing of electricity and fossil fuel must be coordinated as the relativity between them directly impacts the thermal comfort zone electricity consumption wise. Additionally, maintenance opportunity windows for electrical systems within the generation, transmission, and distribution stages arise when weather conditions (especially ambient temperature) are within the thermal comfort zone. Finally, the increase of the share of electricity generation by renewable energy is crucial for any sustainability-based planning to account for short-term demand variations and future scalability.

Abbreviations

CDD: Cooling degree-day; CDF: Cooling demand functions; COP: Coefficient of performance; DSVI: Daily Seasonal Variation Index; E: Total electricity consumption; Eqs.: Equations; EV: Electric vehicles; HDD: Heating degree-day; HDF: Heating demand functions; HSVI: Hourly Seasonal Variation Index; Max: Maximum; MENA: Middle East and North Africa; Min: Minimum; MSVI: Monthly Seasonal Variation Index; NEPCO: National Electrical Power Company; PTI: Population-weighted temperature index; SQP: Sequential Quadratic Programming; ΔT: Temperature difference; σ: Standard deviation; $\overline{E}$: Monthly average electricity load; : Elasticity of function

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Authors' contributions

AM (the corresponding author) and AS conceived of the study, developed the theory, and co-drafted the manuscript. AM and MF processed the raw data, built the optimization codes, and formatted the manuscript. WK contributed to the literature review and the developed theory in addition to the weather database. Finally, IH was the point of contact with NEPCO to get the raw data, revised the theory, and helped in drafting the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The data that support the findings of this study are available from NEPCO but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of NEPCO.

Ethics approval and consent to participate

Not applicable

Consent for publication

All the authors agree to publish the article.

Competing interests

The authors declare that they have no competing interests.

Author details

[1]Mechanical & Maintenance Eng. Department, German Jordanian University, Amman 11180, Jordan. [2]Institut für Technische Verbrennung, Leibniz Universität Hannover, 30167 Hannover, Germany. [3]Mechatronics Eng. Department, German Jordanian University, Amman 11180, Jordan. [4]Department of Mechanical Engineering, Prince Mohammad Bin Fahd University, Al Khobar 31952, Kingdom of Saudi Arabia.

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